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On the selection and design of the proper roof pond variant for passive cooling purposes

Artemisia Spanaki[a,*], Theocharis Tsoutsos[b], Dionysia Kolokotsa[b]

[a] Scholar of Greek State Scholarships Foundation, National Technical University of Athens, School of Architecture, Department of Architectural Technology, 42 Patission Street, 10682 Athens, Greece
[b] Technical University of Crete, Environmental Engineering Department, 73100 Chania, Crete, Greece

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ABSTRACT

The present paper aims to fully summarize the current scientific and technological experience focusing on the comparative characteristics of roof pond variants. The design guidelines and pond characteristics provide the opportunity to make the proper decision of a roof pond variant for cooling purposes. The following systems are under detailed investigation: covered/uncovered pond with/without sprays, skytherm, energy roof, coolroof, walkable pond, wet gunny bags, cool-pool shaded and ventilated pond. A brief background of the motivation behind the creation of the above variants is provided. The advantages and disadvantages of ponds as well as the design considerations and state of the art are discussed. Additionally, in the present study a detailed comparison is performed in terms of effectiveness and cooling demand reduction. A complete set of criteria affecting the choice of the proper roof pond are also analyzed. Finally, a decision support flowchart, is provided based on the various criteria and parameters.

Contents

* Corresponding author. Tel.: +30 2810 326779; fax: +30 2810 326779.
E-mail address: spanakiart@hotmail.com (A. Spanaki).

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1. Introduction

Evaporative cooling utilizes water vapour to cool an air stream and usually is classified into direct and indirect one. The overall process is performed while water absorbs heat from the ambient in order to evaporate, reducing the air temperature. In direct evaporative cooling (DEC) the air is cooled when water in the air stream is evaporated. The latent heat follows the water vapour which is diffused increasing the moisture of the supply air. Indirect evaporative cooling involves heat exchange with another air stream separated by a heat exchanging element (wall or roof). The wet side absorbs heat by water evaporation and hence cools the dry side while no additional moisture is introduced [1].

Roof is the most exposed building element to the sky, providing a wide range of possibilities for building's heat dissipation. Roof ponds represent a promising evaporative cooling technique, resulting to considerable energy savings that may reach even 100% in specific locations. The heat is dissipated through different processes including evaporation, radiation and conduction.

The aim of the present paper is to overview the state of the art of roof pond variants for passive cooling purposes, focusing on the parameters affecting the proper choice under specific climatic conditions and architectural/constructional demands.

The design requirements for the main twelve roof pond variants are sketched and the design guidelines as a function of the cooling effectiveness are provided in detail. Furthermore, a brief analysis to innovative roof pond variants that differ from the investigated ponds is also presented.

The outcomes from several researches, comparing roof ponds are analyzed and collocated, focusing on the most effective, in terms of cooling demand reduction.

Last but not least, the criteria for optimum selection of a roof pond variant are discussed.

The number of roof pond variants is quite high. The different variations divagate in terms of structural and operational characteristics. The present paper aims to present the basic guidelines for decision making regarding the optimum selection according to specific conditions. For this purpose, twelve basic roof pond variants are described in detail. For each one, the function and the design guidelines are analyzed. Fig. 1 provides the description and the functionalities of the various roof pond variants in the cooling season.

There are a number of parameters related to constructional or functional manners that modify the variety of the examined systems. The insulation can be permanent, movable, embedded, floating, can also be completely absent or having a shade instead. The supporting structure can be a metal or a concrete roof. The surface of the water can be free, or the water can be enclosed. In terms of operation, some roof ponds have additional spraying function, mechanical circulation, storage, or special winter operation. Table 1 summarizes the above described characteristics in total.

2. Design considerations and cooling effectiveness on the roof pond variants

2.1. General description and design requirements

Roof ponds can be inexpensively constructed by enclosing water in plastic bags, metal or fiberglass tanks with rigid transparent plastic covers. Movable insulation panels are usually made of 0.05 m polyurethane foam reinforced with fiberglass strands and sandwiched between aluminum skins [2]. This is a standard item marketed as 'metal building insulation'. The system can be supported by a concrete roof, or corrugated metal for better efficiency.

According to Givoni [3], the prerequisite for successful application of roof ponds is that the wet bulb temperature (WBT) should be lower than 20 °C. Further studies that will be described below provide detailed environmental principles for the variety of systems. The present section summarizes the state of the art of roof pond variants, in order to sketch the parameters affecting the proper selection based on specific constructional and climatic considerations. Apart from the description of each system's summer operation, the constructional guidelines and the climatic considerations are provided as a function of the cooling effectiveness achieved.

2.2. Design guidelines as a function of the cooling effectiveness of roof pond variants

2.2.1. Uncovered without sprays

The simplest roof pond is exposed to the ambient without a cover and without spraying system (Fig. 1.1). The water depth is recommended to be at least 0.30 m deep [4,5].

The heat absorbed is inversely proportional to the bottom reflectance. An uncovered pond tends to increase its temperature due to the solar gains until they are compensated by the spontaneous evaporative effect. Typical water temperature fluctuation is around 5 °C [4,5].

The system consumes less water due to the lack of spraying system. Sutton's observations [6] indicate that the surface temperature of a roof, which would reach 65.6 °C without any treatment, can be reduced to 42.2 and 39.4 °C by maintaining an open roof pond of depth 0.05 and 0.15 m, respectively [7].

Furthermore, a thermal model analysis referred to hot dry climate [8], found that passive solar air conditioning of a building with an open pond can be achieved more effectively when there is controlled ventilation. The effects of ventilation rates and timing on controlling the indoor air temperature and consequently the thermal behaviour of a building were found to be significant.

Although open pond is one of the simplest and less effective ponds, it usually results to higher peak roof temperatures reduction in comparison to roof spraying even when the relative humidity is equal to 80% [9–12], but less effective for low relative humidities [13].

Table 1
Comparative characteristics of roof ponds.

	Uncovered with sprays 1	Uncovered without sprays 2	Covered with sprays 3	Covered without sprays 4	Skytherm 5	Energy roof 6	Coolroof 7	Walkable pond 8	Wet gunny bags 9	Cool-pool 10	Shaded pond 11	Ventilated pond 12
Relatively high effectivenes	☑		☑		☑		☑		☑			
Low initial costs	☑	☑	☑	☑	☑						☑	
Null maintenance and function cost		☑						☑	☑		☑	☑
Low water consumption		☑		☑	☑			☑	☑	☑	☑	☑
Low contamination (fixed water protection)						☑	☑	☑	☑		☑	☑
Absence of mechanical operation		☑						☑	☑		☑	☑
Absence of demand For daily attention		☑						☑	☑	☑	☑	☑
Easy to construct	☑	☑	☑	☑	☑				☑		☑	
Widespread know how	☑	☑	☑	☑	☑							
Application in uninsulated concrete roof	☑	☑	☑	☑			☑	☑	☑	☑	☑	☑
Walkability of roof								☑				
Application on tilted roof												☑
Embodied to building' form						☑				☑		☑
Cooling more than one floors						☑				☑		
Winter function			☑	☑	☑					☑		☑

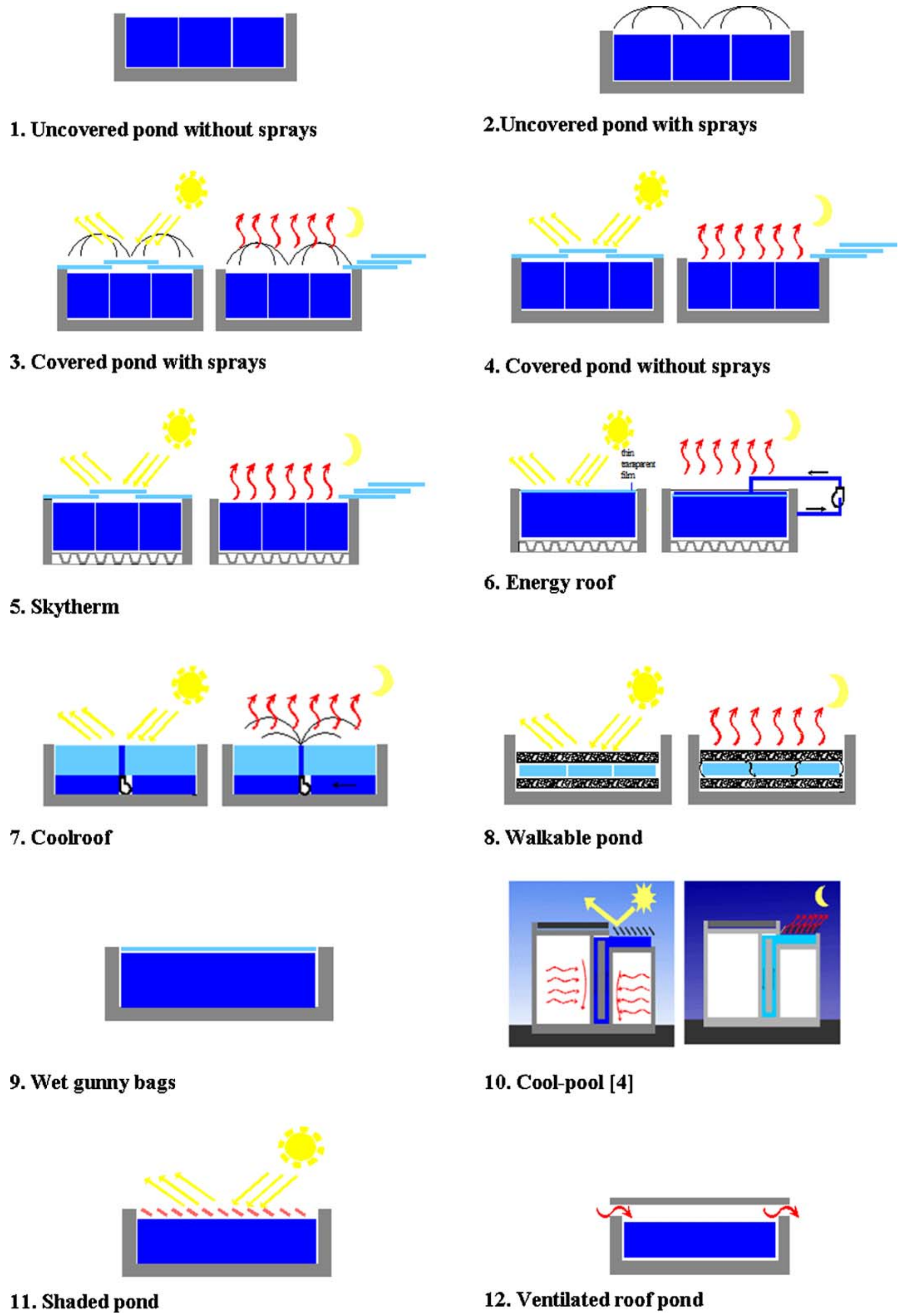

Fig. 1. Roof pond variants.

2.2.2. Uncovered pond with sprays

The open pond can be supported by a concrete flat roof while the spraying system operates during day and night (Fig. 1.2). Droplet radius is recommended to be in the range of 0.005–0.010 m, sprays flow rate from 1 to 1.5 vol/h, while spray height should be at least 0.50 m [4,5]. Spraying should be stopped when the water temperature is 3–4 °C above ambient WBT in order to avoid pond warming.

Limiting spraying operation only during nighttime conserves water and prevents the pond temperature from oscillating around the WBT. Nevertheless, spraying is required to maintain a stable water temperature in shallow ponds (<0.30 m). For deeper ponds the increase in water temperature during daytime is less than 7–8 K, even in warm and sunny conditions [4,5].

Extended research in spraying systems [14] resulted that evaporative roof cooling could reduce the cooling load by 40% for hot dry conditions. The wind speeds up to 3 m/s have no significant effect upon the percentage reduction in heat load due to damping of the

thermal waves within the roof material. Spraying system is usually preferred for larger cooling loads.

Open ponds are often preferable due to their simplicity. Disadvantages of the system are the demand for continuous operation and the susceptibleness to fouling from wind blow dust, leaves, bird droppings, algae and mosquito larvae [3–5].

2.2.3. Covered pond with sprays

This pond is assumed to be covered with movable insulation only during day and spraying is operating only during night (Fig. 1.3). Cover and sprays are assumed to act independently. The covering reduces fluctuation in pond's temperature while spraying lowers the temperature at night; cooling is increased in relation to the sprayed but uncovered pond.

The design recommendations of the spraying system are similar to the uncovered ponds [5,6]. Pond depth in the range of 0.30–0.50 m is adequate for cooling. Additionally, the higher the conductance of the support roof the higher the cooling effect at night [5].

As mentioned above sprays warm the water in the pond when the ambient WBT rises above the pond temperature [4]. This finding suggests that an additional control system should be used to limit and regulate spraying. The cooling rate is higher compared with the uncovered pond with sprays [5].

2.2.4. Covered without sprays

In this variant, the pond (Fig. 1.4) is assumed to be protected from solar radiation by means of an opaque insulated cover, which is in place during daytime only (movable insulation). The cover prevents water overheating, while spontaneous evaporative effects lower water temperature below the average ambient temperature. The system provides a minor cooling effect at all times with negligible temperature fluctuations. The emissivity of coverings' both sides, the solar absorptance of opaque covers as well as the ventilation of the airspace between cover and water surface do not affect the performance [4,5]. The depth of bags is recommended to be in the range of 0.100–0.250 m despite the fact that simulations reveal that the cooling performance is merely insensitive to the water depth [15].

Concerning system's effectiveness, the maximum indoor temperature reaches 21.3 °C when the maximum outdoor is 27 °C [16]. Etzion observed that indoor maximum temperatures can be lowered below the outdoor maximum by 45–50% of the outdoors' range.

The system can be used with inverted operation in winter for heating but demands further costs for the cover's automatic operation. A variation of the system uses a gap between the pond's insulation and the roof' thermal mass in which the cooled water from the pond can be canalized and circulated dissipating heat from the space below, while the pond is covered [3].

Testing the thermal performance of a pond filled with water with 0.10–0.15 m depth seated on a metal deck with movable insulation [17] in a tropical climate, showed that it is possible to keep the indoor temperature below the outdoor temperature even in a hot and humid climate. The roof pond is possible to reduce the thermal load through the external surfaces from 41 to 66%. The average cooling potential experimentally obtained is 19.4 W/m^2 K and 24.0 W/m^2 K during August and January respectively, which in terms of daily removed heat is equal to 465 Wh/m^2 and 577 Wh/m^2 for the respective period. Under clear sky conditions, 16% of the total cooling is due to evaporation. The cooling capacity of the roof pond reduces as the wind velocity increases, however, the indoor temperature decreases indicating that the wind convective cooling effect of the walls is more important than the water heat gain by convection.

Considering ease of operation, round the year use and the requirement of water, the shallow pond tank with movable thermal insulation over the roof has been found best for cooling of structures and better comfort conditioning in arid areas [18].

2.2.5. Skytherm

The skytherm system, the most well investigated roof pond was patented by Hay in '60s. The differences of skytherm compared to the above-described covered pond are:

- The supporting roof of skytherm is a metal deck while the aforementioned variant is used for concrete roofs.
- The water is enclosed to bags in order to allow the evaporation effect to be performed only by a spraying system optionally used (Fig. 1.5).

The metal roof provides better thermal coupling with the space below and amplifies the night cooling by radiation to the night sky while its corrugated form increases the area exposed to the sky.

Ponds, usually constructed by plastic bags, may be provided with integrally connected air-cells for better efficiency or can be constructed by metal or fiberglass tanks with rigid transparent plastic covers but these are more expensive. Panel tracks and supports should also be designed in a way that the panels form an assembly as tight as possible when closed [2,19]. The panels open and close manually or by automatic control, and a mechanical guidance and drive system physically relocates the panels in either position. To keep the transfer of heat from the pond to the metal deck as higher as possible, it is desirable to waterproof the top of the deck with a thin plastic sheet like a double laminated polyethylene carefully sealed at the edges, a fiberglass sheet or a thin coat of asphalt emulsion [19]. It is important to paint the underside of the metal deck since galvanized metal is a poor radiator when bare. Because the ceiling radiates at a relatively low temperature, it can be painted any color [2]. The main disadvantage of skytherm and movable insulation panels is attributed to the inconvenience caused by the unreliability of the panels' moving motor.

The performance of the system appears to be satisfying. In a nine-month test performed in hot climate, no additional auxiliary heating or cooling systems are used [20]. Based on an air conditioning coefficient of performance of 4.7 and an electrical generation efficiency of 30%, this cooling effect is equivalent to the use of about 2 barrels of oil during the cooling season. Another study [21] performed in hot arid climate indicates that the indoor temperatures can be maintained below 30 °C in summer while the maximum dry-bulb temperatures are above 40 °C. A study assessing winter infrastructure for heating showed a 86% heating demand reduction in mild winter [19].

Several skytherm buildings have monitored and evaluated, in the hot climate of California. As reported in the Marlatt Report, the interior temperature of buildings kept within the range of 20–23.5 °C throughout the summer. With outdoor maximum of about 34 °C, the indoor maximum is around 21 °C. Further tests on a small building (25 m^2) showed that the maximum temperatures of the building with the modified skytherm are lower than those of the conventional building by about 6 °C in July and by 8 °C in October [22–24].

Another variation of the skytherm is a pond placed under a pitched roof which is conventionally insulated on the north side and has clear insulated glass on the south side. The comparison of the specific variation with 0.20 m water depth with other passive techniques (direct gain, Trombe-wall, waterwall, sunspace) indicated that the roof pond strategy creates the smallest temperature fluctuations during the heating period which is equal to 0.2 °C in cold climate [25].

An analysis of the periodic heat transfer of a roof pond in both winter and summer gives interesting considerations for the selection of appropriate thicknesses [26]. For hot humid climate a roof pond system comprised of water-concrete-insulation in ascending order of thickness in the summer, and a combination with a descending order of thickness in the winter, is thermally more desirable. For a typical cold climate, the roof pond system with an ascending order of water-concrete-insulation thickness is more appropriate. Nahar et al. [18] reported that 0.10 m of water depth is sufficient to get a favorable temperature. Nevertheless, a former analysis [27] indicates that there is no benefit in increasing the water depth in values greater than 0.05 m of roof pond with regards to reducing the roof temperature for hot–humid climate. The 0.05 m of water depth of roof pond with movable insulation is appropriate for reduced water demands and for improved comfort conditions in arid regions.

Furthermore, the summer performance of a building can be further improved by allowing vapours to be released to the atmosphere [28]. Released water vapours at high pressure a large amount of pond's evaporative heat is carried into the atmosphere.

2.2.6. Energy roof

In this system, water is contained within a parapet and the thermal insulation floats on the water under a thin, transparent plastic film. The roof basin is filled with approximately 0.40 m water and is supported by a corrugated metal ceiling [5]. For summer cooling, water is pumped at night to a circulating tube, which allows flow in a thin layer above the insulation layer where is then cooled by long wave radiation at night (Fig. 1.6). A water spray promotes evaporative cooling at the upper surface of the plastic film. The system is patented by Pittinger and White in the USA [4,5]. Experiments have been also carried out by Yellot et al. [3].

2.2.7. Coolroof (floating insulation)

In this variation, the water is circulated at night over the floating insulation (Fig. 1.7). Cool water temperature should be about 1–2 K above the average ambient wet bulb temperature (WBT). The ceiling temperature in case of concrete roof should be about 2 K above the water temperature. The insulation panels must be impermeable to water, i.e. extruded polysterene [16].

According to the tests of Bourne in hot climate, who invented Cooloof in 1980, the indoor temperatures during daytime are around 25 °C with the outdoor maximum of about 37 °C. During the daytime the water is heated by about 5 °C but its maximum water temperature is almost the same as the outdoor air minimum temperature. Even when the roof pond is not coupled directly (conductively) with the interior space it can provide in an arid region during summer effective cooling [22]. Givoni proved that the temperature patterns of the system are almost identical to the ventilated pond despite the different mechanisms of heat transfer. Coolroof resulted to slightly more stable temperature patterns, especially during heat waves. The experiments' period included a heat wave, where the outdoor average temperature increased from 26 to 32 °C [16,22].

The performance of the system is also tested extensively, with thermal models, in the arid regions. With maximum outdoor temperature of 35 °C, the maximum temperature of a test control cell used is 33 °C, the pond's water maximum is 22 °C and the indoor air temperature of the cooled cell is 24 °C [22,23]. Another study held in a hot humid climate indicated that the indoor maximum temperature has lowered by about 2 °C [22,29].

2.2.8. Walkable pond

The described system has an insulation panel within the pond. During summer, the pond is filled with water to a level about 0.03 m above the insulation. The insulation plates divide the water into two layers – upper and lower – with gaps permitting thermosyphonic circulation (Fig. 1.8). The system is applicable specifically for buildings with reinforced concrete flat roofs in desert regions with mild winters (minimum temperatures usually above freezing) [16].

The fixed floating insulation is cheap and easy to apply, and the thickness can be such as to avoid the heating effect of the solar radiation. It can though, inhibit heat dissipation at night, and a spray system becomes essential [4,5].

According to Givoni [16], the indoor maximum temperatures are lowered by about 2 °C compared to a house without any treatment on the roof. Another experiment [30] held in a hot climate showed that the average indoor temperature is about 28 °C, when the outdoor temperatures fluctuates between 30 and 42 °C, thus it is stabilized at a slightly lower level than outdoor minimum temperature.

The system has the advantage of the provision of useful area in the roof. Unfortunately, there is a lack of experience in construction and estimation of system's performance.

2.2.9. Roof pond with wet gunny bags

The system suggested and tested by Tang et al. [31,32]. It consists of gunny bags placed on a grid or mesh with polystyrene strips or other floatable materials attached underneath (Fig. 1.9). The gunny bags are used to intercept solar radiation, and dissipate the received radiation and heat gains from the interior of buildings through the roof by means of water evaporation, convection and thermal radiation. The optimal water depth is 0.20 m for metal-decked roofs and about 0.05 m for a concrete roof.

Experimental results [31] showed that the system performed slightly better than a pond with movable insulation. The reason is probably the thermal stratification of the water inside the pond. Simulations also indicate that the system produces more stable indoor temperature and higher heat dissipation through the roof compared to a roof covered with wetted gunny bags. In addition, this system is less sensitive to the absorptivity of gunny bags compared to the wetted gunny bags, due to water's increased heat capacity [15,31,32]. The system is easy to be built and does not demand control.

2.2.10. Cool-pool

The system consists of an open water pond shaded by sloping louvers, and supported by a concrete roof (Fig. 1.10). Cooled water is then pumped to a storage tube in the building below through concentric thermosyphon pipes in which the cooled water flows slowly downwards. The water which is warmed by thermal exchange with the indoor air rises back to the pool again [3,5,33]. Karen Crowther and Melzer patented this system in 1979 in the USA.

The pool can lose heat by evaporation whenever the vapour pressure of the atmosphere is lower than that of the pool water, in addition to radiative losses [3,5]. The maximum cooling occurs for maximum shading and minimum relative humidity [33]. Choice of suitable protective louvers proved to be a major task, and a chevron (L-shaped) design is found to offer adequate shading and allow greater span widths than could be attained with flat 45° slats, according to Hammond tests. The same experiments showed that a small, well-insulated room could be kept between 20 and 25 °C during summer period where the afternoon outdoor air temperature consistently exceeded 38 °C [3]. The system has similar performance compared to unshaded ponds in terms of temperature but with less water consumption [34]. The amount of heat removed per unit of evaporated water is higher than water film and roof pond [33]. Cool-pool can also be used for winter passive heating; tubes can be designed to function as a water wall by placing them behind south glazing and by blocking circulation with the roof pond. The system does not require daily attention [21] but has a high main-

tenance cost in comparison with other evaporative cooling options of similar effectiveness [3].

2.2.11. Shaded pond

In the shaded-pond system, a shade over the pond is provided to cut off solar radiation using a permanent structure with a configuration similar to the venetian blinds (Fig. 1.11). Thus, while the water is exposed to wind, the direct exchange of radiation between the sky and the water is prevented [21]. The system can be supported either by a concrete or metal roof. There are limited applications of the system in spite that according to a theoretical model developed by Yadav and Rao [21], the temperature inside the building can be maintained below 30 °C when maximum ambient WBT is over 40 °C for hot and arid climates and even for the concrete roof. Shaded pond without thermal coupling to the interior is ineffective if the infiltration is more than 5 air changes per h (ach) [21]. It should be noted that the effect of the humidity on the shaded pond is similar to that of skytherm [21].

A comparison [35] between a building using shaded roof pond under hot humid conditions to a second one with increased thermal mass under hot arid conditions without any treatment to the roof, showed that both strategies are highly recommended for arid locations. The comfort analysis yielded similar results for each strategy, with increased indoor comfort levels and limited cooling demand for the increased-mass building and no cooling demand for the shaded pond. The shaded pond alone drops the night-time temperatures to values lower than the lower adaptive comfort limit. It is therefore suggested that both systems could be used in combination, thus reducing the daily indoor temperature fluctuations and maintaining indoor temperatures close to the WBT.

2.2.12. Ventilated roof pond

Ventilated roof pond has a secondary lightweight insulated roof over the pond, shading the water. The cover is permanently in place and well separated from the water level by a ventilated air layer (Fig. 1.12). With this configuration, the radiant cooling potential is lost, but the convective and evaporative effects dominate. In some locations such configuration is sufficient to remove all the thermal loads without the need of an extra spraying system [4,30].

The advantage of ventilated pond lies in the fact that there is no demand for any operation except closing the openings and draining the water in winter [16]. It can also be applied in a tilted roof where the lower surface of the cavity is kept wet In this case, the water replenishment is needed only for 1–2 times per month [36]. Disadvantages are the requirement for the construction of two roofs and the lack of experience since the technique is recently introduced in the market.

Ono [37], suggested in 2002 an alternative ventilated pond, where large openings between the ceilings and the upper floor slab permit airflow. The ceiling (pan) made of 5 mm thick FRP (fiber reinforced plastic) is filled with 0.03 m water. The water replenishment is needed only 1–2 times per month. Experimental testing of the thermal performance showed that the water temperature is about 1–2 K above WBT on average, and the ceiling surface temperature about 1 K above the water temperature. The heat flow from the ceiling to the habitable space is about $-25\,W/m^2$ [37].

In terms of efficiency, water temperature of ventilated pond should be about 1–2 K above the average ambient WBT and well below the daytime air temperatures even in humid regions, according to Givoni [16,22]. The ceiling temperature in the case of concrete roof should be about 2 K above the water temperature. The water temperature almost follows the average ambient WBT, thus the system provides a very effective cooling in dry regions with maximum WBT not exceeding 24 °C even when daytime temperature exceeds 40 °C. As mentioned above, the ventilated pond results to indoor temperatures practically identical to the cool-roof system (with floating insulation), despite the very different cooling mechanisms [22]. Further experimental testing [38–40] held in full-scale rooms cooled by a ventilated roof pond in the hot humid climate. The roof pond is shaded by a reflective horizontal plate with the air flow in the space between the cover and the water forced by extractor fans. During the first two weeks, the pond is kept empty, the indoor temperatures the outdoors' average. After that, water is added to the pond and the indoor temperatures drop significantly. After the initiation of the cooling effect the daily indoor maximum is 3 °C below the outdoor maximum temperature and about half of the diurnal range.

Numerical simulations [36] for a ventilated inclined roof with a wet lower surface of the cavity, showed that this component is an effective protection against solar gains. Nevertheless, the values of the heat flux obtained show that the component is aimed at industrial or commercial buildings where vast roof areas are available and where the cooling problems are of greatest concern. The maximum performance can be obtained if a solar chimney is also applied in the building.

According to measurements, for hot and dry climate the pond stabilizes the interior temperatures while rises and drops are diminished [41]. Adding a fan to increase evaporation, result further decrease of indoor temperatures. The fan also reduces water temperatures in the pool by a much larger margin than the interior, suggesting that treating the remaining exterior surfaces would increase the effect of roof cooling. Furthermore, in real-life cases where most spaces have a larger proportion of roof to wall, roof cooling would be even more effective and drops the cooling load by around 29%.

2.3. Innovative roof pond variants

Alternative roof ponds variants have been suggested, allowing evaporative cooling. The "Sunny South Model" [42], provides both heating and cooling. The system utilizes a shallow roof-pond solar heat collector with a reflector to intensify solar input and uses "Pancake" under-the-floor heat storage. The warm water from the roof-pond drains each night to the under-floor "Pancake" heat storage area where it warms the floor and living space. During the summer the roof-pond helps minimize day-night temperature extremes by absorbing excess heat during the day and liberating it at night. In spite that the system was expected to bring more of the good life to the have-nots at low cost, yet to determinate widespread acceptance.

An innovative pond protected by an aluminum sheet proposed in 2003 composed of a concrete ceiling over which lies a bed of rocks in a water pool [43]. Over this bed is an air gap separated from the external environment by an aluminum plate. The upper surface of this plate is painted with a white titanium-based pigment to increase reflection of a radiation to a maximum during the day. At night, the temperature of the aluminum sheet falls below the temperature of the rock bed mixed with water. Water vapour inside the roof condenses and falls by gravity. This heat pipe effect carries heat outwards and cold inwards. Heat exchange is improved by radiation between two humid internal surfaces. Numerical calculations show that the cooling produced by the system is significant and the mean air temperature in the room may be kept a few degrees above the minimum nocturnal outdoor temperature throughout the day. However, the maximum indoor air temperature is observed at sunset. This could further be lowered by allowing ventilation of the building during the evening.

An alternative hybrid pond with singular protection recently proposed by Juanico [44–46]: the system consists of a metallic base with an upper-level step to support the structure. A solid watertight metallic base for the water chamber is covered with a double glazing cover similar to that of a flat solar collector. The large water

inventory on the roof is connected by piping to the storage tank that feeds a standard hot-water in floor heating system, including a boiler. A rolling awning is extended above the previous assemblage on summer days and winter nights. A third air chamber providing suitable thermal insulation on the roof is created, together with the double glazing. On summer nights a secondary water pond is generated onto glass panes in order to cool it by means of evaporation and thermal radiation to the sky. The temperature can drop down to 10 °C below ambient temperature [18]. Summer daytime the cooled water is pumped into the metallic roof to get indoor cooling by free convection. In the meanwhile, this water pond is protected from solar radiation by extending the rolling awning; a swallow pond of 0.05 m depth eliminates more than 50% of house heat load [27].

Furthermore, a rolling awning which is a curtain always extended between two rolling axes has been proposes for water protection [44]. The number of contiguous covers is increased from one to three, one always extended and the other two coiled in the rolling axes. The roof can be changed according to different environmental conditions. The function of the opaque curtain is to block sun irradiation during summer days and to minimize heat losses during winter nights. It also could be manufactured as an inflatable device connected to a home air compressor. By inflating this curtain when it is extended, heat losses could be reduced significantly during winter [47]. The function of the transparent curtain is to increase the solar absorption and reduce convective heat losses. This last characteristic can be enhanced by using an inflatable curtain, or a cellular plastic polymer [48].

3. Comparative performance of roof pond variants

3.1. Introduction

The present section aims to perform a holistic comparison of the roof pond variants. Even though efficiency is one of the most important parameters, there are issues limiting the widespread application of the most effective ponds, such as high water consumption, demand for mechanical equipment, etc. For this purpose, the present analysis focuses on parameters related to the cooling efficiency together with constructional and operational characteristics.

Therefore the comparison is based on the following criteria based on the existing research work:

1. The thermal coupling between the roof pond and the building.
2. The integration and interaction of the roof pond with the building.
3. The role of spraying.
4. The role of roof pond's cover.

3.2. Achieving thermal coupling between pond and the building

The first comparison criterion is the thermal coupling between the roof pond and the building which is influenced by the roof's construction characteristics and more specifically the roof's material and depth.

Metal roofs result to better thermal coupling between the pond and the building. This explains why that metal skytherms are considered to be more effective than the concrete ones. Thinner concrete roofs reduce more the cooling and the heating loads than the thick ones. The metal skytherm is more affected by the water depth than the concrete skytherm in which the thick roof slab also acts as a heat storing mass thus fading the heat-storing effect of water [19]. Furthermore, Energy roof is also supported by a metal roof, but there are not any related investigations, assessing the role of the supporting roof material.

3.3. Cooling more than one floors with pond "embodied" to building

The aim of the present section is to compare the various roof ponds versus their ability to be integrated into the building.

Cool pool system is a part of the building, since the cooling and heating effect is transferred to the building's interior. As a result, the net amount of heat lost by convection, radiation and evaporation from water surface to the surroundings is taken from the room interior, whereas in other roof pond variants the part of the incident solar radiation which is absorbed by the roof surface also adds to the cooling load of the building. This results in a relatively lower indoor air temperature and consequently a smaller water requirement in a cool-pool system. Thus, cool-pool is more efficient than water-film and roof-pond techniques, since the amount of heat removed per unit of water evaporated is more, for hot humid climate [33]. Additionally, the cool-pool effectiveness is not affected by a reduction in roof area covered by the water. The cool-pool system therefore appears to be the legitimate choice for buildings having a limited roof area, and for climates where water is not freely available, and high initial costs is not an issue.

3.4. The role of spraying and pond cover in system's efficiency

In this section the following criteria are analyzed:

1. The roof pond cover's effect.
2. The spraying effect.

Regarding covers, shaded pond is an advantageous system due to the lack of any operational mechanism. On the other hand skytherm demands daily operation, resulting to a better effectiveness of the roof pond shading device, even in hot humid climate [21]. This is because the pond water exchanges thermal radiation with the night sky in the skytherm system whereas, in the other, it exchanges with the shading device, which is at the ambient temperature. In spite of this, the effectiveness of the skytherm and shaded ponds are equally good. Skytherm is not very effective from the comfort point of view but its thermal performance is better than the shaded-pond system.

Roofsool project [4,5] is focused on the study of natural cooling techniques involving the roof. The results of the sensitivity studies analysis are presented below in descending order of performance:

- uncovered pond
- pond covered during daytime
- pond with sprays working all time
- pond covered during daytime and sprayed at night
- pond covered during daytime and sprayed all the time

The best operating conditions are given by the use of a cover during daytime and of sprays at night. In terms of both temperature and internal heat flux the performance of pond covering during daytime and sprays during nighttime has a sensible effect in comparison to other tested variants. Uncovered pond seems to have the less cooling effect and the greater declination in comparison to the rest variants [4].

Furthermore, sensitivity analysis in the covered pond showed that the use of a pond cover during daytime prevents overheating of the water, while spontaneous evaporative effects lower water temperature to well below the average ambient temperature. A slight cooling effect is achieved at all times with negligible temperature fluctuations. The emissivity at either side of the covering

Table 2
Comparative performance of roof ponds; each row represents a different study.

Comparative performance of roof pond variants			Reference
Worst	Median	Best	
	Open pond	Shaded pond	[50]
Covered pond without spraying	Covered pond with continuous spraying	Covdered pond with nightime spraying	[4,5]
		Roof pond with wet gunny bags	[15,31]

and ventilation of the airspace between cover and water surface has negligible effect while water temperatures and cooling effect showed little sensitivity to variation in the solar absorptance of the covering. The cover is recommended to be an opaque one.

On the other hand, uncovered pond has a little difference in performance with droplet radius in the acceptable range 0.5–1.0 mm. Limiting spray operation to night-time can prevent the pond temperature from oscillating around the web-bulb. The same design considerations of the spraying system are also valid for covered pond with sprays. The cover was in place during daytime, whereas spraying was at night. The covering reduces fluctuation in pond temperature while spraying lowers the temperature at night, and as a result cooling is increased in relation to the sprayed but uncovered pond. Assessing the effect of the sprays working during daytime highlighted the fact that the spraying warms the water in the pond when the ambient wet bulb temperature rises above the pond temperature. This finding suggests that some form of control needs to be fitted to prevent such occurrence.

The lack of any operational demand for water pond protection together with high efficiency would be ideal. Roof Ponds with Gunny Bags (RPWGB), seem to fulfill these criteria, since it appeared to be more effective in comparison to the former ones. Results by simulations indicated that RPWGB performed slightly better than Roof Pond with Movable insulation [15] providing slightly lower indoor temperature and slightly higher heat flux nearly all of the day. The difference in indoor air temperature between two cases is negligible.

Last but not least, according to Tang's and Etzion's experiments [31], all the ponds which were compared were ranked according to performance (from best to worst): pond with towels floated on it (RPWGB) and pond with movable insulation, shaded open pond, open pond, covered pond.

As a result, in terms of energy efficiency, pond with movable insulation can be further improved with spraying, resulting higher water consumption. Pond with towels floated on it (RPWGB) is also more effective than pond with movable insulation, and also more advantageous since does not demand any mechanical equipment.

4. The overall comparison of roof pond variants; the parameters affecting the proper choice

There are two fundamental considerations for effective use of roof ponds for cooling purposes:

- The wet bulb temperature (WBT) of the air should be lower than 20 °C [3].
- The roof should be watertight, able to support 200–400 kg/m^2.

Both theoretical and experimental studies have been held on a specific climate and defined conditions. Therefore, the results of a study cannot be generalized, except if a number of studies held on different conditions conclude the same results.

Table 2 tabulates the comparative performance of roof pond variants, according to heretofore literature. Each column of the table represents a different study. Thus, the performance of an open pond can be further improved if shaded, while pond with movable insulation can be further improved by spraying at night. As a result, shaded pond, roof pond with gunny bags, and pond with movable insulation and spraying at night seem to have higher efficiency in comparison to conventionally former ponds. Nevertheless, there is not a research estimating the relative performance of these three above-described systems.

4.1. Recommended water depth

The depth of the water is critical on the supporting ability of the roof. Greater water depths are preferable in new buildings, where extra attention is paid in order to support the extra load. Table 3 presents the adequate water depths in a variety of options.

4.2. Setting criteria for making the relevant choice of the proper roof pond variant

Certain parameters can encourage or discourage the use of a certain variant of a roof pond for cooling purposes. The most critical is the effectiveness of the system, in terms of cooling demand reduction. Nevertheless, some of the most effective systems may probably result to inconvenience due to the high water consumption, or the demand for daily attention (e.g. movable insulation system). On the other hand, the proper choice of a roof pond variant may be affected by certain specific demands, like the demand for walkability or the application on tilted roof.

Table 1 summarizes all characteristics in order to resolve option capabilities. Consequently, the parameters affecting a choice are the following:

Cooling more than one floors
Application in uninsulated concrete roof
Absence of demand for daily attention
Walkability of roof
Low contamination
Winter function
Easy to construct (availability of materials and devices)
Low initial costs
Null maintenance and function cost
Widespread know how

Some of the above parameters describe certain conditions while other may be characterized as advantages or disadvantages. As a result, the proper choice is affected both by the certain construc-

Table 3
Recommended water depths for different roof pond variations.

	Roof pond	Adequate water depth (m)
1	Open pond	0.30
2	Roof pond with movable insulation and spraying system	0.30–0.50
3	Roof pond with movable insulation without spraying system	0.10–0.25
4	Energy roof	0.40
5	Wet gunny bags	0.05 (0.20 for metal roof)
6	Skytherm	0.05–0.10

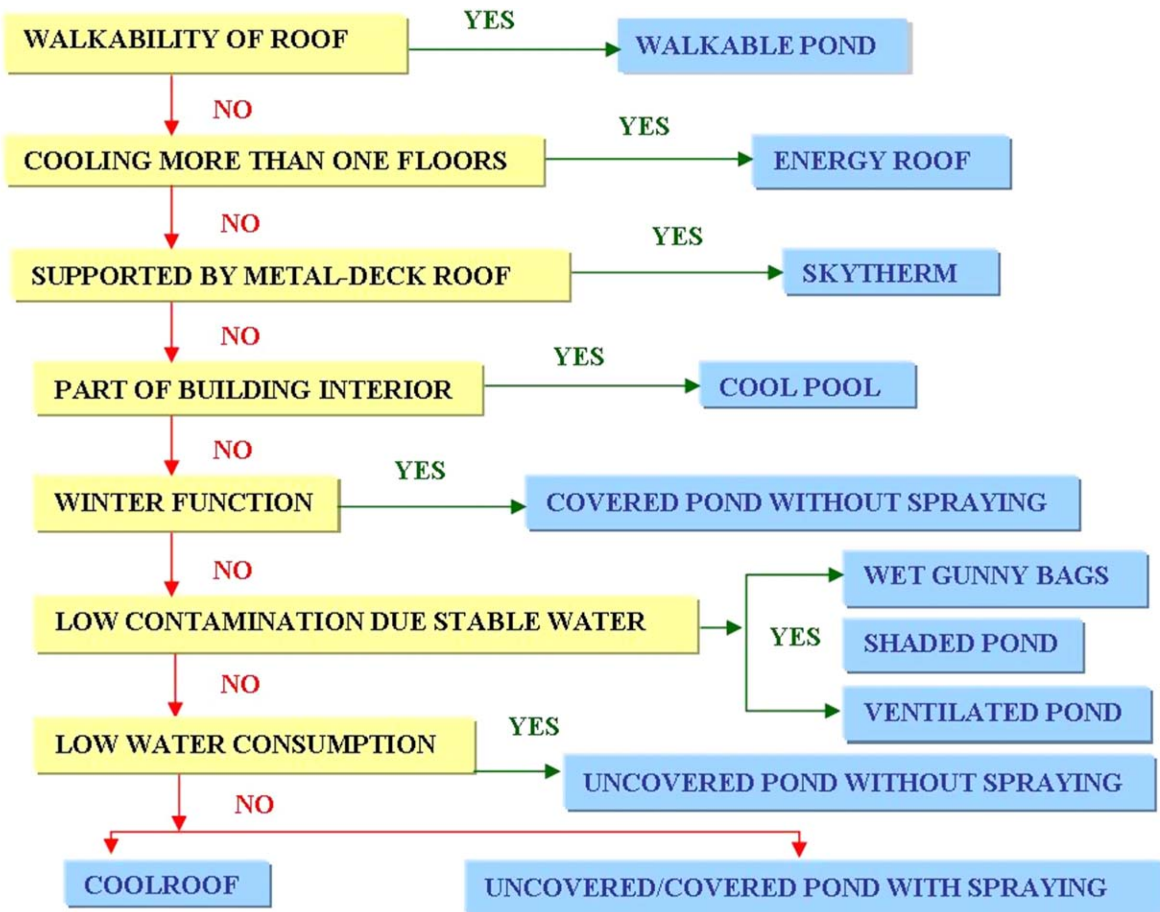

Fig. 2. Choice of the proper roof pond option according to selected criteria.

tional and functional conditions, and the importance that is given in specific demands (e.g. water consumption, initial costs, etc.).

Fig. 2 provides a way to make a decision, based on the basic parameters affecting a choice. In spite that the diagram cannot include all parameters, represents an easy way to make a step by step choice.

5. Conclusions

Roof ponds are widely considered as one of the most favorable technique for passive cooling in climates that encourage evaporative and radiative cooling. The only constructional consideration is a watertight roof able to support 200–400 kg/m^2. The performance of systems is independent of building orientation while most of them provide heating as well. Additionally, most of them are easy to build with low initial costs, since water is cheap and widely available. Even when there is a lack of water, brackish water can be used.

Nowadays, there is a number of projects aim to limit cooling demands by means of passive cooling techniques in roofs worldwide. The heretofore literature in roof ponds resulted that, shaded pond, roof pond with gunny bags, and pond with movable insulation and spraying at night and seem to have the best efficiency in comparison to conventionally former ones. Nevertheless, the lack of experience by the construction company and the inconvenience due to contamination caused by the stable water has unfortunately limited their application in buildings.

The provision of a roof pond with the highest possible cooling efficiency in comparison to the lowest maintenance and inconvenience due to stable water would probably resulted a more favorable passive cooling technique.

Passive solar systems for space heating and cooling, as well as passive cooling techniques when used in combination with conventional systems for heating, cooling, ventilation and lighting, can significantly contribute to the energy saving in the buildings sector [49]. Roof ponds, as an effective passive technique can strongly contribute to energy demand reduction, in building's sector.

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